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TECHNICAL REPORT ON SUPPORT TO THE AIR FORCE RESEARCH LAB (AFRL)
In support of award #FA9550-04-1 0459

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Feb, 2006

Summary:

In support of AFRL's space vehicles directorate I conducted a series of observations and analysis. Beginning with three visits to AFRL/VS at Kirtland AFB, NM lab personnel led by Dr. Babu Singaraju we identified a critical space superiority objective was the ability to detect and study small objects (microsatellites) at Geosynchronous altitudes. The PI (Simon Worden) in concert with faculty and staff at the University of Arizona and the Hawaii High Performance Computing Center were able to plan a series of observations using the Steward Observatory MMT telescope and its Adaptive Optics system of several large commercial Geosynchronous satellites. This data was additionally post-processed using methods developed at the University of Arizona and the Hawaii High Performance Computing Center. These results showed that small microsatellites (less than 1 square meter) could be easily detected at GEO altitudes. Further work to refine these methods have been proposed for direct AFRL funding. The details of this work are given below.

1. INTRODUCTION

In the past decade numerous nations have begun developing and launching so-called microsatellites for a variety of purposes. While these systems began as "toys", the technology has developed rapidly – to the point that significant military capability may be obtained from satellites in the 100 kilogram category. Most of these new military microsatellites are designed for various types of data collection – in particular optical images and electronic intelligence. Moreover, most to date have been restricted to Low Earth Orbit (LEO) orbits. However, this is changing.

The University of Surrey's Surrey Space Technology Ltd. (SSTL) has been at the forefront of both microsatellite development and technology transfer to other nations. Until recently this expertise has focused on LEO systems. Recently SSTL has developed and is marketing a small satellite bus for deep space applications, the Geostationary Mini-Platform (GMT).[1] This bus weighs several hundred kilograms and has an optical cross section of about 2-4 square meters.

In addition to Geosynchronous Earth Orbit (GEO) small and microsatellites SSTL and others have made significant progress on so-called "nanosatellites" – systems weighing a few tens of kilograms at most and having cross sections of a few hundredths of a square meter. Such systems would have visual magnitudes of 17-19th magnitude or fainter. While new wide field space surveillance search systems such as the DARPA/MIT Lincoln Lab Space Surveillance Telescope (SST) and the AFRL/University of Hawaii PanSTARRS system are configured to find such objects there remain some significant challenges presented by these new developments. In particular, a microsatellite in close proximity – a few hundred meters – from a large GEO satellite would be invisible to conventional tracking telescopes as its signal would be swamped by the much brighter seeing disc of the large satellite.

Current and proposed space surveillance systems, even with adaptive optics systems are unable to obtain useful images of GEO objects. Even a fully adaptive telescope of a few meters diameter has an optical resolution of ten meters or worse at GEO. Moreover, these smaller telescopes collect insufficient photons to detect very small objects such as nano-satellites near larger GEO assets.

[1] See the Surrey Space Technology Ltd. website for details: http://www.sstl.co.uk/

The University of Arizona is developing extremely large ground-based telescopes. In addition to our existing 6.5m diameter MMT on Mt Hopkins, we are building the Large Binocular Telescope (LBT) on Mt Graham. This telescope with twin 8.4 m mirrors has an equivalent optical aperture in one dimension of 22m and can achieve 1 m or better image quality in that dimension. We have begun work on the Giant Magellan Telescope (GMT) with seven 8.4 meter mirrors providing an equivalent optical aperture of 25m.

Using our existing adaptive optics system and the MMT we have shown how this new generation of very large telescopes can be used to make useful images of GEO objects. In addition we show how this approach might detect extremely small objects near larger GEO and other deep-space satellites.

2. THE STEWARD OBSERVATORY ADAPTIVE OPTICS (AO) SYSTEM

The Steward Observatory Adaptive Optics (AO) system was constructed over the previous six years under a grant from the Air Force Office of Scientific Research (AFOSR). During this period the system was developed, constructed and installed on the 6.5m MMT on Mt Hopkins, AZ. This system encompasses a number of unique features with significant advantages over alternative approaches. Fig. 1 illustrates the basic system concept. Detailed discussions of this system are available in [1,2,3].

The unique aspect of our approach is to embody the adaptive element in the secondary mirror (Fig. 2). This is accomplished by constructing the adaptive secondary as a very thin (2mm thick) deformable mirror 642 mm in diameter. This thin mirror is restrained by an in-plane structure. Actuation is done via 336 moving magnet actuators with a nominal air gaps of 45 μm between the magnets attached to the thin mirror and the actuators. The precision reference body against which the actuators work is a 50mm thick aluminum cold plate. This plate and associated optics is cooled to ambient temperatures via 7 cooling channels to allow for thermal infrared operation.

Wave front sensing is accomplished through the adaptive optics top box mounted at the MMT Cassegrain focus and shown in Fig. 3. The natural "guide star" is acquired and fed to a 12x12 Shack-Hartman wave front sensor. We calculate slope values across the wave front which are then filtered to correct approximately the first 50 Zernike modes of the wave front which are then used to modulate the deformable secondary mirror described above. The wavefront sensor update occurs at 550 Hz, but can be slowed down to 100 Hz for fainter guide stars. The higher speed correction is possible for guide stars to V=12 magnitude, while the slower speed can extend correction capability to V=15. Thus the system can work using typical large GEO satellites as the guide star. The acquisition field of the AO system is a 60 arcsecond diameter field. Low airmass targets are ideal, although the system will operate at low elevations.

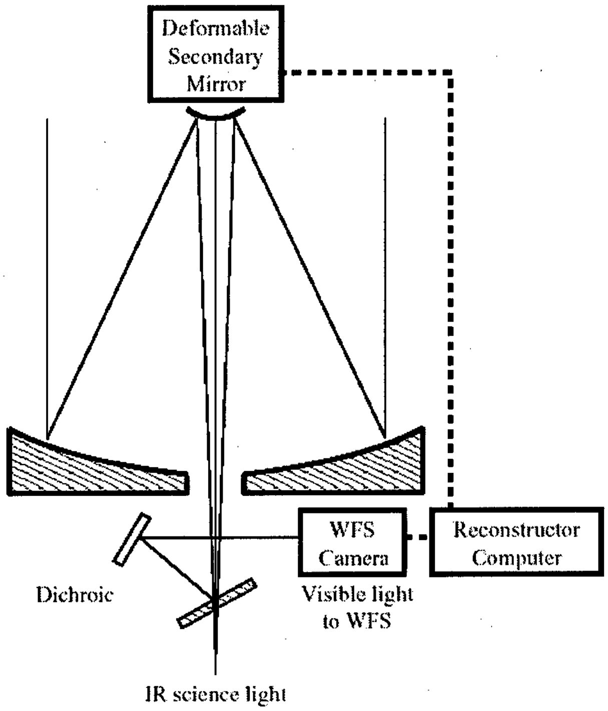


Fig 1. Schematic Diagram of the University of Arizona MMT AO system.

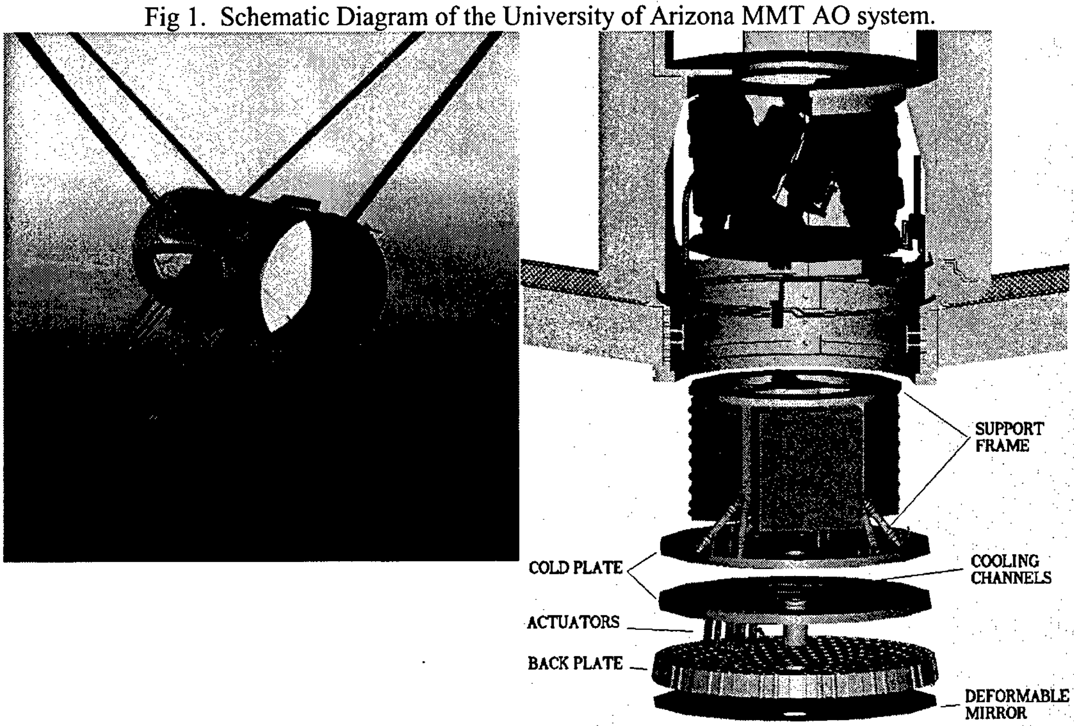


Fig. 2. Adaptive Optics deformable secondary mirror from the MMT telescope (left) and schematic diagram of the secondary assembly (right).

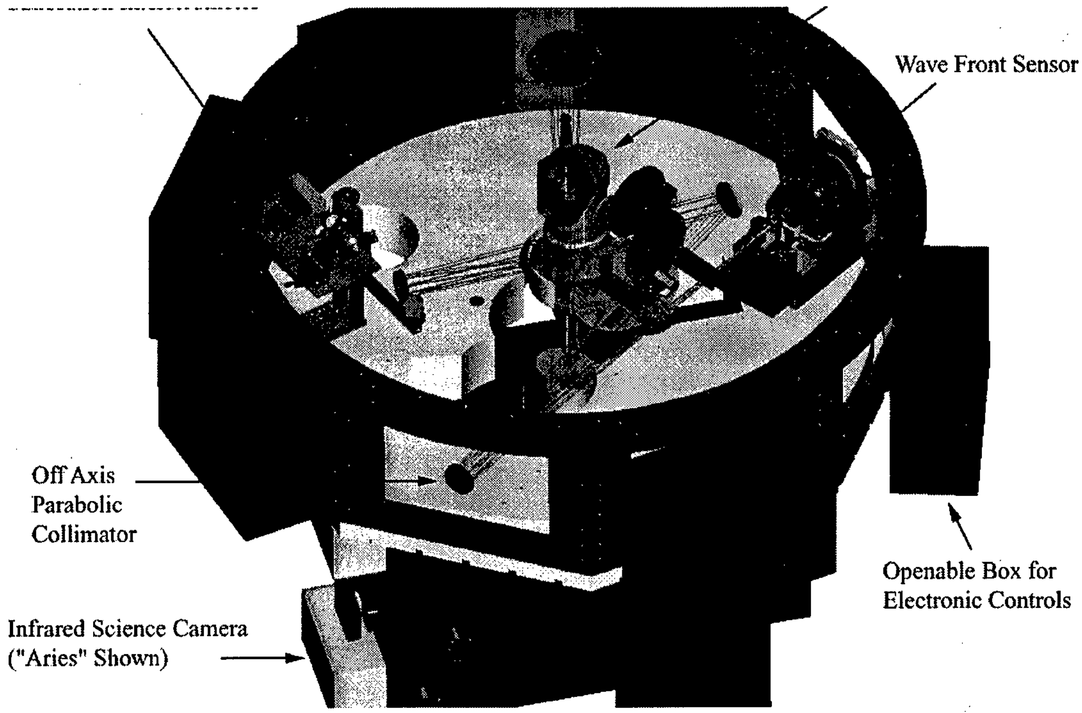


Fig. 3. Wavefront sensor “Top Box” from the MMT AO system.

Fig. 4 illustrates the advantages of our approach. In conventional AO systems a series of mirrors take the light from the main telescope and re-collimate it. From this point a portion of the light is split-off to drive the wavefront sensor which in turn drives a small deformable mirror. The light is then re-focused onto the science instrument. This approach entails a number of additional reflective, defocusing and focusing optics as well as removing some light for the wavefront sensor. Our approach removes much of this complexity and light loss and gives us 2-3 times shorter integration times for equivalent results in the near-infrared bands (Lloyd-Hart et al, 2000).

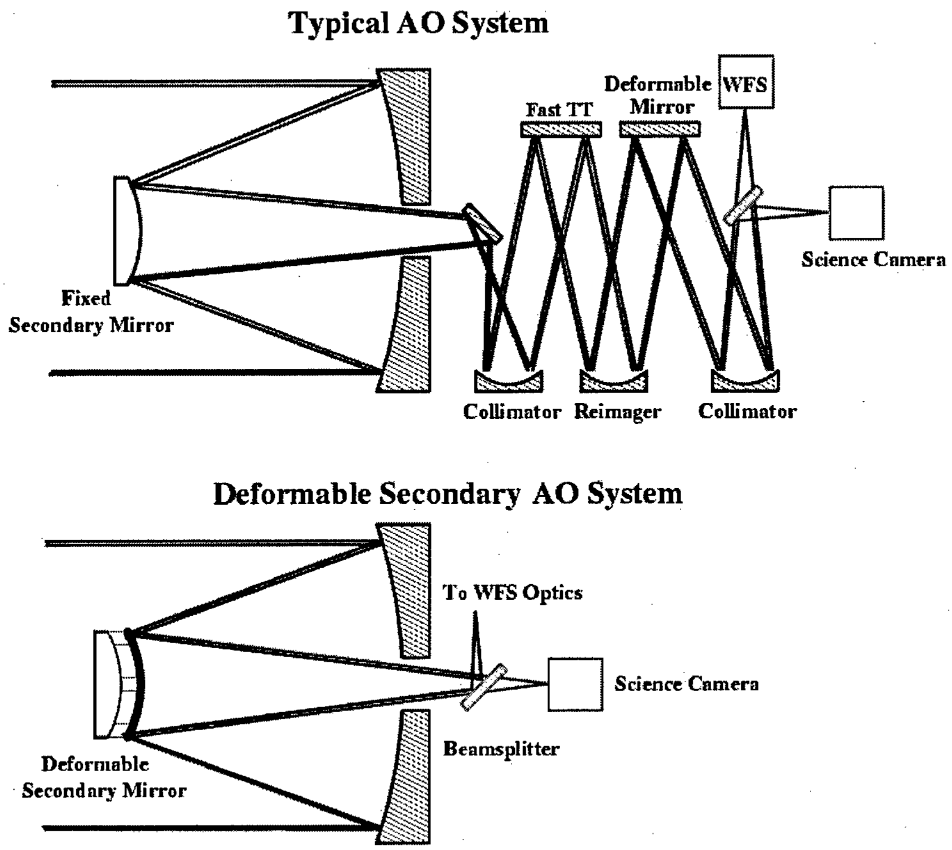


Fig. 4. The differences between a conventional AO system (top) and the MMT AO system (bottom). The MMT AO system is simpler and provides thermal background up to factor of three smaller than the conventional system.

The ARIES imaging system is designed to obtain scientific data in the near-infrared spectral region (H and K spectral bands – 1-2.5 μ wavelength). The ARIES science instrument camera module forms the last element in the AO chain. Converging light from the adaptive secondary mirror enters the ARIES thermal dewar directly to minimize thermal background. A dichroic entrance window reflects wavelengths <1 μ into the "Top-Box" shown in Fig. 3 for wavefront sensing while the longer wavelengths are transmitted and form an initial cooled focal plane (f/15) 25 cm below. Over a 50 arcsec diameter field, the 1-2μ light from natural field stars is picked-off and sent to a global tip/tilt wavefront sensor for active centroid measurements. An Offner relay produces a sharp, achromatic pupil image for thermal baffling and reimages the focal plane onto the slit/dichroic assembly. A 10242 pixel HgCdTe (1-2.5 μ) camera provides diffraction-limited imaging. We typically achieve 20-30% Strehl in the spectral H-band using bright stars. Fig. 5 shows the type of images we obtain from the system.

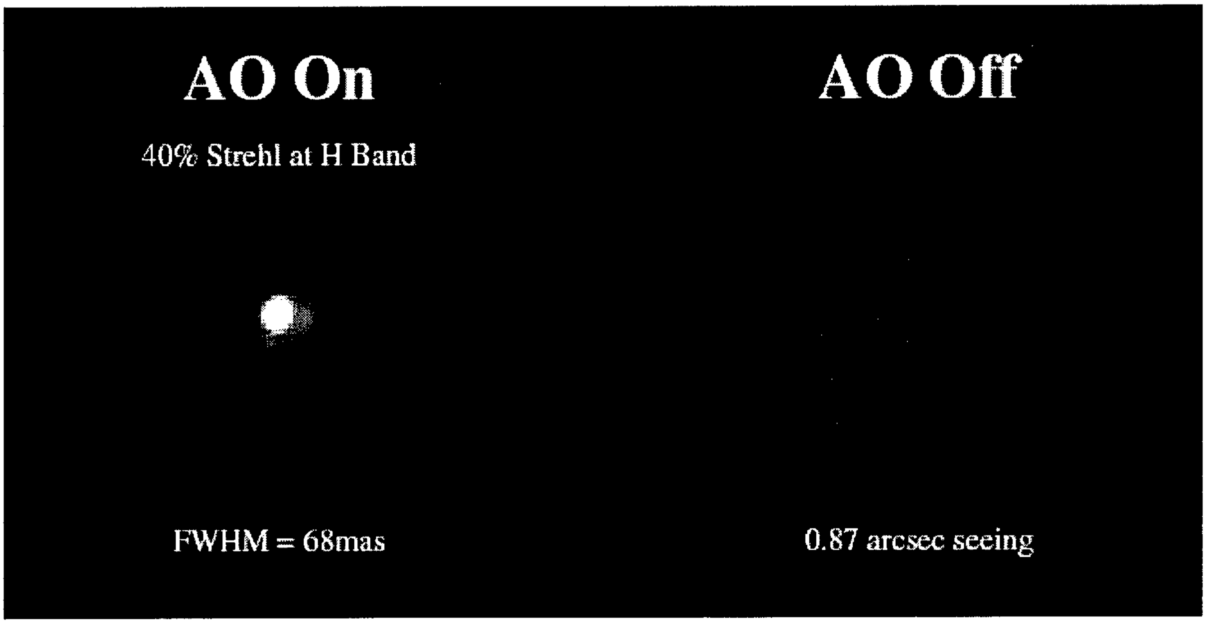


Fig 5. Examples of MMT AO performance in the near infrared H band. With typical seeing of slightly better than 1 arcsec (right) the AO system produces nearly diffraction-limited performance of 68 milli-arcsec (left).

3. DEMONSTRATING THE SYSTEM ON GEO SATELLITES

To demonstrate the capabilities of the AO system we obtained a data set on two bright GEO satellites on the evening of April 30, 2005. The two satellites we chose to observe were the Canadian communications satellites Anik F-2 launched 17 Jul 2004 and the MSAT M-1 launched 20 Apr 1996. Diagrams of the ground truth for these two satellites are shown in Fig. 6 and Fig. 7. Particularly the ANIK F-2 represents an interesting test target as it has solar panels extending almost 50m in one dimension (48x8m size). By comparison MSAT M-1 is 21x19m. A series of data at low airmass consisting of several exposure times in the spectral H band (1.6 μ) was obtained for each satellite along with corresponding point source star data. The results of this run are shown in Fig. 6 and Fig. 7 for these two objects – exposure times for the satellite image shown was 30s. The results show both objects to be clearly resolved. We note that the diffraction limit for the MMT in the infrared corresponds to about 10 m at GEO – so only relatively large satellites are observable with this approach. Nonetheless we believe these may be the first direct ground-based optical images of GEO satellites.

The Images are narrow-band (10% of H band window) and 30 s integration: equivalent to a 3 s exposure in H band. Anik F2 was H=9.3 magnitudes at the time of the observations – making it among the brightest objects in the GEO belt, a reason for using it as an optimum test target. The apparent halo at 0.5" away in the AO-corrected image is approximately 200 times fainter than the satellite. From this we determine that the noise level at 0.5" appears to be ~500 times fainter than Anik F2, or approximately H=16. This noise appears to be random and from photon statistics. Longer integrations can easily achieve fainter detection limits. Previous photometry has shown that ARIES can achieve S/N of 10 in 10 s in H band on a source of H=19.6. Thus we believe microsatellites could be easily detected with this system as discussed in a later section of this paper.

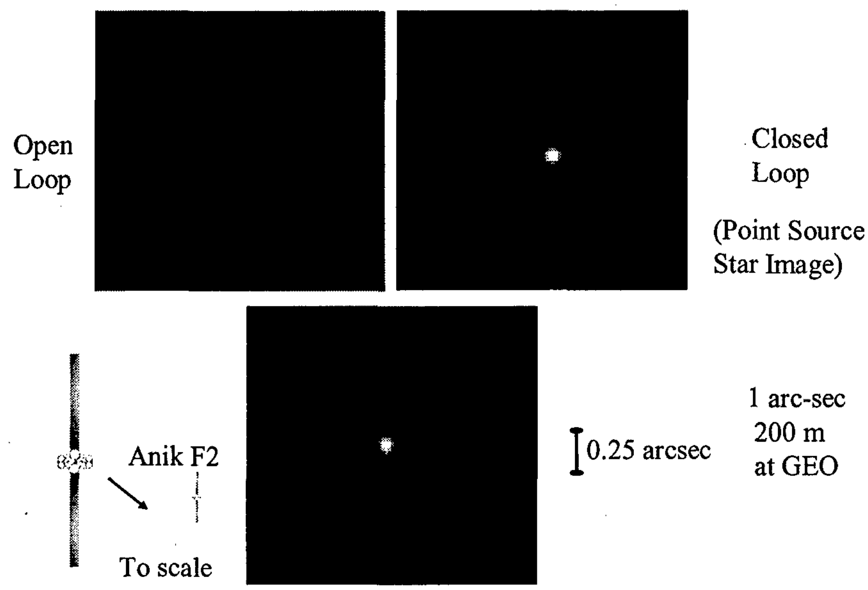


Fig. 6. Results of MMT AO imaging for the ANIK F-2 satellite. The top images show the performance on an unresolved point source. The bottom image is the AO corrected image of ANIK F-2. The elongated solar panels, 50 m in diameter are clearly visible in this data. The satellite is about 0.25 arc-seconds in angular extent in the long direction. By comparison the uncorrected I arcsec seeing disc extends over 200 meters.

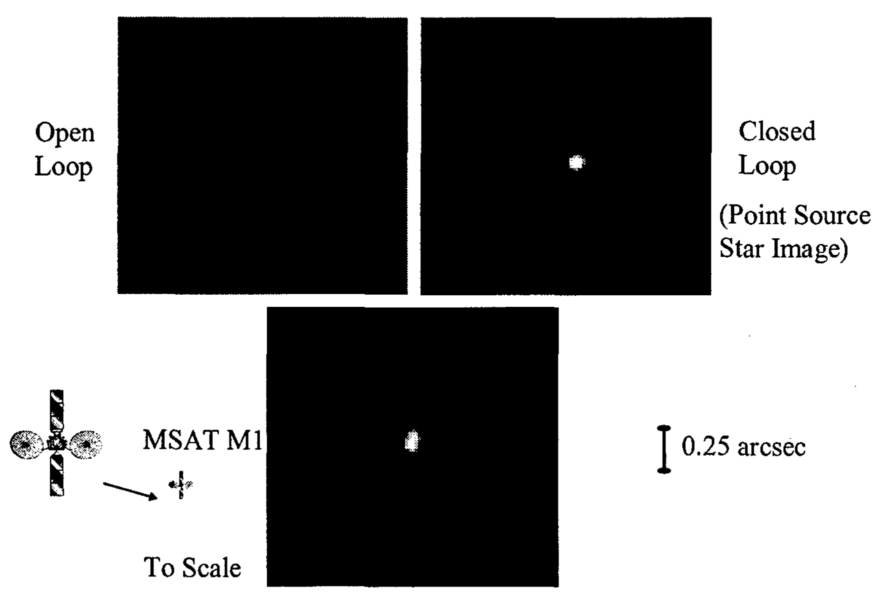
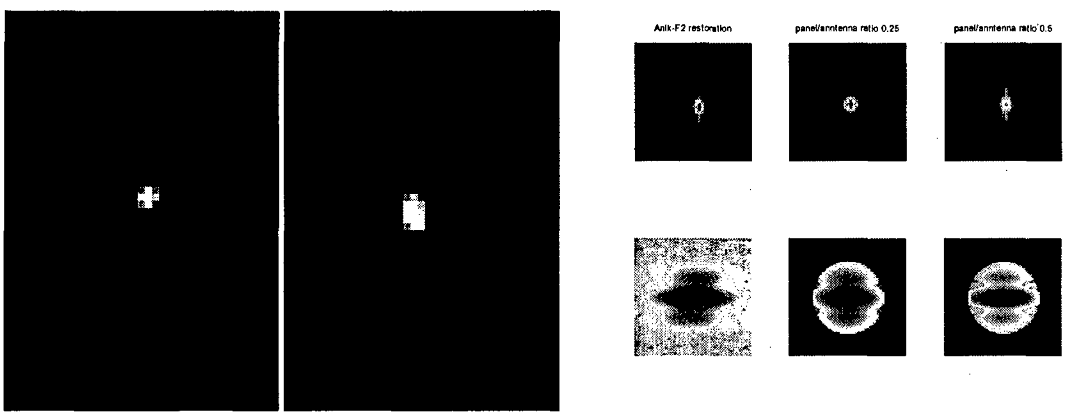


Fig. 7. Results of MMT AO imaging for the MSAT M-1 satellite. The top images show the performance on an unresolved point source. The bottom image is the AO corrected image of MSAT M-1. The extended solar panels and antenna are visible in this data. The satellite is about 0.12 arc-seconds in angular extent. By comparison the uncorrected I arcsec seeing disc extends over 200 meters.

4. POST PROCESSING

While these images are interesting in their own right, they contain considerable residual noise and interference and do not represent terribly useful image content as they stand. However, our team has developed sophisticated post-processing methods that are applicable to AO-corrected image data ([4,5,6]) and which can provide further improvements in the image resolution. We used these methods to post-process our satellite data. First multiple images were registered and co-added. An estimate of the noise was then derived and the images Wiener filtered. The Wiener filtered estimate of the target object was then used as the initial estimate for the object in a multi-frame blind deconvolution processing (MFBD) of the data using the algorithm described in [4]. The resulting estimates of the point spread functions from the MFBD analysis were then used in the deconvolution algorithm described in [6] to provide the restorations shown in Fig. 8. Simple modeling of the target objects shows that the restorations in Fig. 8b are close to diffraction limited (e.g., see Fig.9). Moreover, the level of restoration noise is very low, an important requirement for detecting low intensity objects in the background as discussed in the next section.



0.25 arcsec = 50m

Fig. 8. Post-processed images of ANIK F-2 and MSAT M-1. Compare these images with the raw AO images and ground truth shown in Fig. 7 and Fig. 8. These images exhibit a final resolution close to 5 m at GEO, a considerable improvement over the raw AO results. The right image above represents model results. The first column is the restored ANIK-F-2 model and its power spectrum. The second column is a model with a panel to antenna ratio of 0.25 and the third column is for a ratio of 0.50. Our restored image best matches the actual satellite profile providing confidence in our approach.

5. DETECTION LIMIT OF IMAGING APPROACH

Since one of our objectives is to detect small objects near large ones we have examined our data to determine how well a small object might be detectable in the vicinity of a bright object such as ANIK F-2. We artificially placed an unresolved object in the field of the AO corrected image with a factor of 30 and 100 less surface brightness. As this object is unresolved and ANIK F-2 is resolved its actually represents objects 100 and 300 times less bright than ANIK (15^{th} and 16^{th} magnitude) respectively. These would be objects with optical cross sections of .3 – 1 square meters – typical sizes for today's microsatellites. The results are shown in Fig. 9. For the latter two test images a radially smoothed component has been removed. The accompanying object is clearly visible in both cases. Based on our results we believe objects up to ten times fainter (19^{th} magnitude) and cross sections of a few hundredths of a square meter would be visible with minimal post-processing.

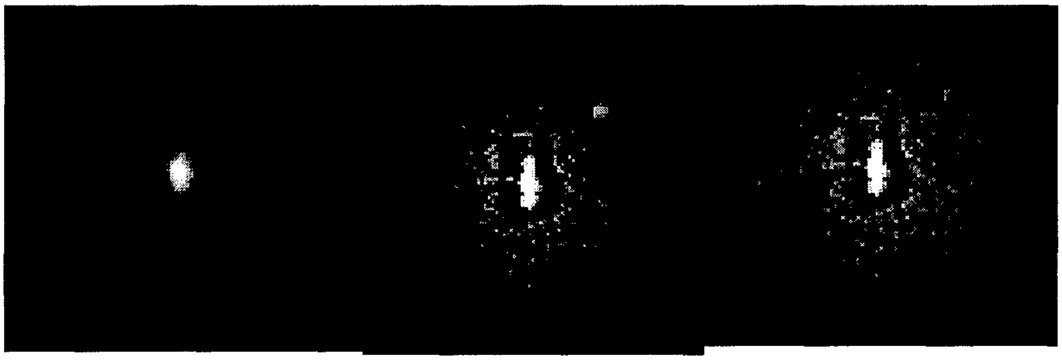


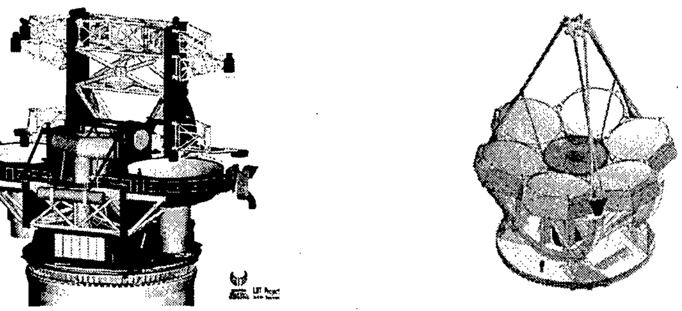
Fig. 9. Results of simulations of the ability of the MMT AO system to detect microsatellites placed near to a large satellite such as the ANIK F-2. The left image is a raw AO output for ANIK F-2. For our simulations we removed a radial profile to minimize scattered and uncompensated residual light. The middle image shows our simulation for a 1 square meter microsatellite and the right image shows the results for a 0.3 square meter object. In both cases the object is 100 m from the large satellite and would be completely invisible in conventional uncompensated imagery.

6. LARGER TELESCOPES

While the performance of the MMT AO system is impressive, particularly with respect to detecting faint objects, its image quality is insufficient to perform much in the way of useful analysis on GEO satellites. To perform such analysis would require optical systems capable of sub-meter resolution at GEO. Fortunately systems capable of this resolution, operating at shorter wavelengths than the 1.6 micron H band, are now under development and construction.

The University of Arizona is responsible for optical component development for two next generation telescopes utilizing 8.4 meter primary mirrors made in the University of Arizona Mirror Laboratory – Fig. 10. The first of these telescopes, the Large Binocular Telescope (LBT) will begin operation in 2006 and consists of twin 8.4 meter primary mirrors on a single mount.[2] Corrected beams from the two primary mirrors can be combined to form an image corresponding to a single 22.8 x 8.4 meter telescope. We have also begun development of the more ambitious Giant Magellan Telescope (GMT) [7-] which will consist of seven off-axis 8.4 meter primaries on a single mount. This system is capable of imaging performance close to that of a single filled aperture 24.5 meter telescope. The GMT should begin operation in the first half of next decade. AO systems utilizing adaptive secondary mirror systems are planned for both telescopes.

[2] See the web site http://medusa.as.arizona.edu/lbto/ for extensive information on the LBT.



Large Binocular Telescope (LBT)	Giant Magellan Telescope (GMT)
Twin 8.4 m primary mirrors	Seven 8.4 m primary mirrors
22.8 m baseline in 1 dimension	24.5 m baseline in 1 dimension

Fig. 10. Next generation 20-30 m class telescopes under development by the University of Arizona.

To illustrate the performance of these systems we show in Fig. 11 the type of image resolution possible for ANIK F-2 with these two systems. Using 1 μ wavelengths 1-meter resolution is clearly obtainable. Post processing may be able to improve this performance by up to a factor of two.

49x8 m Sat. 6.5 m MMT 2x8.4 m LBT 7x8.4 m GMT

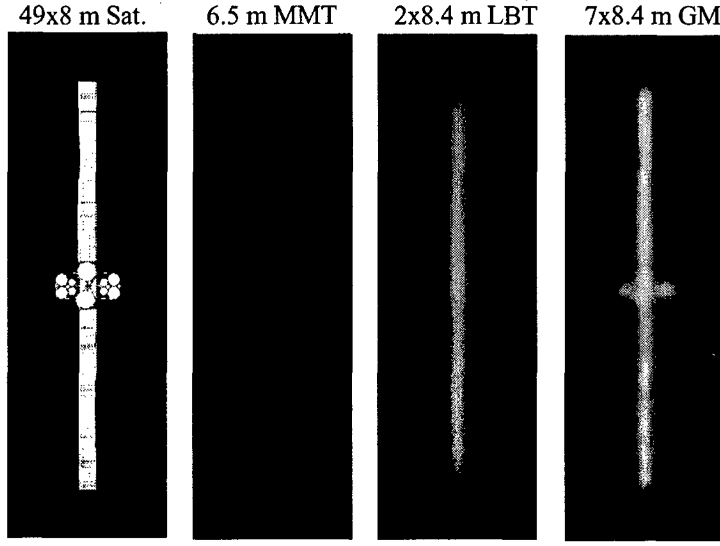


Fig 11. Simulations of image resolution possible for a large satellite (ANIK F-2 – on left) for the 6.5 m MMT, the 2 x 8.4 m mirror LBT and the 7 x 8.4 m mirror GMT.

7.0 SUMMARY AND CONCLUSIONS

We have shown that large astronomical telescopes equipped with adaptive optics systems can obtain useful images of deep space satellites. The next generation of telescopes, in the 25-30m diameter range will be able to obtain optical images with sub-meter resolution on satellites in GEO orbits. Such data can provide an interesting new dimension to space situation awareness.

In addition to direct imaging applications, adaptive optics images of large GEO and other deep space satellites might also reveal the presence of very small, so-called microsatellites in the vicinity of larger objects. Such objects can be difficult to detect using other ground-based methods.

8.0 ACKNOWLEDGEMENTS

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